0038-075X/87/1434-0278$02.00/0
Soil Science
Copyright © 1987 by The Williams & Wilkins Co.

April 1987
Vol. 143, No. 4
Printed in U.S.A.

PROISOTROPIC AND PROANISOTROPIC PROCESSES OF PEDOTURBATION

DONALD L. JOHNSON,[1] DONNA WATSON-STEGNER,[3] DIANA N. JOHNSON,[2] AND RANDALL J. SCHAETZL[1]

Because pedoturbation processes (soil mixing) occur in all soils in varying degrees during the course of their evolution, mixing processes should be assessed within the larger context of soil genesis. Soils may be viewed as evolving along two pedogenic pathways that operate concurrently: a progressive pathway that includes processes, factors, and conditions that promote ordered, differentiated and/or deep profiles; and a regressive pathway that promotes disordered, simplified, rejuvenated, and/or shallow profiles. Pedoturbative processes that disrupt, blend, destroy, or prevent the formation of horizons, subhorizons, or genetic layers, such that simplified profiles evolve from more ordered ones, are *proisotropic* and function within the regressive pathway. Pedoturbative processes that form or aid in the formation and maintenance of horizons, subhorizons, or genetic layers and/or promote increased profile order are *proanisotropic* and function within the progressive pathway.

Ten forms of pedoturbation are recognized. Hypothetical and real examples of how proisotropic and proanisotropic mixing processes affect soil profiles are presented. The examples demonstrate that both the *form* of pedoturbation and the *texture* of the parent material largely determine whether the ensuing morphology of a soil expresses order or disorder. A particular form of pedoturbation may produce a disordered profile in one soil or polypedon, but a more ordered profile in another. This can be true not only for different soils on a landscape, but also for the same soil at different times during its evolution. Homogeneous or heterogeneous geologic deposits may be pedologically organized, or reorganized, via proanisotropic pedoturbation to express profile order and in certain cases may produce spatial patterning and microrelief. Surface stone pavements and armored surfaces, subsurface stone lines and stone zones, and upper profile biomantles can thus be formed.

Pedoturbation is a synonym of soil mixing (Hole 1961). Mixing processes occur in all soils to various degrees and scales during their evolution. They are, thus, pedogenetically very important processes. The cumulative effects of pedoturbation may be reflected in soils and soil landscapes at two levels: (1) within soils as distinct morphologic imprints and structures, such as pedoslickensides, krotovinas, stone zones, various "flame structures," genetic horizons, and broken or interrupted horizons; and (2) at ground surface in microrelief and/or distinct spatial patterns, such as animal mounds, stone pavements, patterned ground, and gilgai. Imprints and structures range from microscopic to macroscopic; some features are observed only through thin-section microscopy; other features, such as genetic horizons and layers, are clearly visible in road cuts and other exposures.

Hole (1961) originally listed nine processes of pedoturbation (e.g., faunalpedoturbation, or mixing by animals, and floralpedoturbation, or mixing by plants). Wood and Johnson (1978) simplified the nine terms by omitting the syllable *pedo* (Table 1). The addition of *impacturbation* is based on observations of mixed or otherwise disturbed soils exposed in the upper walls of some impact craters, for example as at Odessa, Texas.[4]

Hole also grouped the various pedogenetic factors and processes in a conceptual scheme consisting of two pathways: "(a) propedanisotropic factors and processes which differentiate soil horizons; and (b) propedisotropic factors and processes which disturb soil horizons (as in pedoturbation), or which impede the formation of soil horizons" (Hole 1961, p. 377). In our opinion, this theoretical scheme represents a significant advance by providing a different and very useful view of pedogenesis (the "dual pathways" scheme forms the conceptual nucleus of a new soil evolution model whose essentials are outlined below).

---

[1] Dept. of Geography, Univ. of Illinois, Urbana 61801.

[2] World Heritage Museum, Univ. of Illinois, Urbana 61801.

[3] 8702 Aspen Circle, Parker, Colo. 80134.

Received for publication 13 Dec. 1985; revised 14 April 1986.

[4] As of mid-1985, more than 101 certain or probable and 46 possible impact sites had been identified, with 4 or 5 new ones being annually reported in recent years (McHone, 1986, pp. 95–103, and personal communication, 1985).

TABLE 1

Ten pedoturbation processes[a]

Process	Soil-mixing vectors
Aerotubation	Gas, air, wind
Aquaturbation	Water
Argilliturbation	Swelling and shrinking of clays
Cryoturbation	Freezing and thawing
Crystalturbation	Growth and wasting of salts
Faunalturbation	Animals (burrowers especially)
Floralturbation	Plants (treefall, root growth)
Graviturbation	Mass wasting (creep, solifluction, etc.)
Impacturbation	Comets, meteoroids
Seismiturbation	Earthquakes

[a] Modified and expanded from Hole (1961).

The placing of pedoturbation in the propedisotropic pathway implies that morphologically simplified or homogenized profiles are a natural consequence of mixing processes. Because pedoturbative processes do not, however, always produce morphologically simplified or disorganized profiles, soil mixing must be assessed within the larger context of soil genesis.

Soil genesis may be viewed as proceeding along two alternating, coacting pathways that are progressive and regressive: the *progressive* pathway includes processes, factors, and conditions that promote organized, differentiated, and/or deep profiles; whereas the *regressive* pathway includes processes, factors, and conditions that promote simplified, rejuvenated, and/or shallow profiles (Johnson and Watson-Stegner 1987). Pedoturbation is a common component of both pathways.

The following working definitions and concepts are offered as an attempt to refine and extend the original formulations of pedoturbation within a theoretical framework of soil evolution. Pedoturbative processes that form or substantially aid in forming or maintaining horizons, subhorizons, or genetic layers and/or cause an overall increase in profile order are *proanisotropic* and part of the progressive pathway. Pedoturbative processes that disrupt, blend, or destroy horizons, subhorizons, or genetic layers or impede their formation and cause morphologically simplified profiles to evolve from more ordered ones are thus *proisotropic* and part of the regressive pathway. (In this usage the prefix *pro* means "tendencies toward.") Thus pedoturbation that promotes a simplified profile from one that was previously more differentiated, even though a new horizon or genetic layer may form in the process, is by definition proisotropic. On the other hand, if pedoturbation leads to the formation of one or more horizons or genetic layers, but evidence for overall profile simplification is neutral or absent, as is very often the case, the process is assumed to be proanisotropic. The nuances and particulars of these definitions will become apparent to the reader in later sections.

In the next section we demonstrate the validity and usefulness of these concepts, first by presenting some hypothetical examples of soil mixing, followed by review of some actual examples. The actual examples are of soils that express surface microtopography or patterning or whose morphologies have been imprinted or overprinted by various pedoturbative processes. The review of hypothetical and actual examples is not intended to be comprehensive, but to highlight the concepts presented here.

PROISOTROPIC AND PROANISOTROPIC PEDOTURBATION: HYPOTHETICAL AND ACTUAL EXAMPLES

The general category of pedoturbation not only reflects the functioning of soil-mixing agents and vectors, but also the adjustments made to such mixing by the soil system. Therefore, the degree to which a given soil has experienced proisotropic (regressive) or proanisotropic (progressive) pedoturbations must be determined on the basis of observed and measurable morphological attributes and properties, augmented when necessary by laboratory characterization data. As the examples below will show, for many pedoturbated soils the principal determinants of morphological order or disorder and/or of spatially expressed surface patterning are the *range* in particle sizes of the parent material in conjunction with the *specific form* of pedoturbation that occurred or is occurring.

The effects of some proisotropic pedoturbations, such as tree uprooting in nongravelly soils, may be such that they are clearly expressed in a single profile or pedon. To identify the effects of proanisotropic pedoturbation, however, it is usually necessary to study the soil or soils in a spatial and, if possible, temporal context, as in topo- and chronosequences of soils and surfaces. In this way, some understanding of past, present, and probable future pedogenetic pathways is gained (Figs. 1 and 2).

Figures 1 and 2 schematically represent several examples of how proisotropic and proanisotropic pedoturbations can function regressively and progressively to promote soil disorder or order. (Unless otherwise specified, or indicated graphically—e.g., Fig. 2i–m, the mineral soil in these hypothetical cases is assumed to consist of nongravelly fine fraction material.) The T_2 stages of Figs. 1 and 2 depict generalized horizonation characteristics as observed in some modern profiles. The T_1 stages depict former morphologies of the same soil prior to the passage of an unspecified period during which pedoturbation occurs. In real field settings, however, firm evidence of prepedoturbation (T_1) morphologies often may be skimpy or absent (i.e., soils are palimpsestlike, but pedogenic change and overprinting in some soils *completely* obscure or erase preexistent morphological states). In such cases, deciding whether a modern (T_2) profile reflects predominantly proisotropic or proanisotropic pedoturbation becomes, like much of science, a matter of observer interpretation and bias. Also, Hole (1961) noted that a process "... might appear to be distinctly propedisotropic, yet it is simultaneously propedanisotropic ..." depending on the pedogenic context.

Hypothetical examples of proisotropic pedoturbations

In Fig. 1 all four profiles show a decrease in profile order and an increase in morphologic simplicity, i.e., fewer horizons or subhorizons at T_2 than T_1. Pedoturbation is, thus, by definition of the proisotropic kind. The first example (Fig. 1a) shows how a soil with three horizons at T_1 (an A/B/C profile) can regress to one with two horizons at T_2 (an A/C profile). In deep, nongravelly soils that are forested, tree uprooting produces such regressed, simplified soils; if uprooting is frequent enough and widespread, a landscape biomantle forms that is expressed by hummocky microrelief.

The next three examples (Fig. 1b–d) show how soils with four horizons at T_1 (A/E/B/C profiles) can regress to soils with three horizons at T_2 (A/B/C profiles). In Fig. 1b the A, E, and Bt1 horizons are mixed together, resulting in an overthickened A horizon and a thinned Bt horizon by T_2. Such profile simplification processes have been attributed to faunalturbation by earthworms (Langmaid 1964).

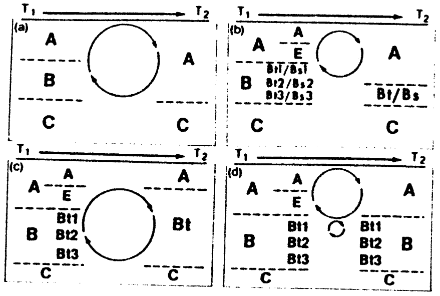


FIG. 1. Four simplified, hypothetical schemes showing aspects of proisotropic pedoturbations. Each diagram shows how horizons are reduced and profiles simplified during a period T_1 to T_2. Other permutations are possible.

In Fig. 1c the E horizon at T_1 is destroyed by T_2 at the expense of an expanding Bt horizon, a process that some investigators have suggested or implied is due to subsoil argilliturbation (Dan and Singer 1973; Muhs 1980, 1982; Soil Survey Staff 1975, p. 377).

Figure 1d is worthy of note, because it shows how different forms of mixing may occur simultaneously in topsoil and subsoil horizons of the same soil by different pedoturbations, one functioning proisotropically, the other proanisotropically. After T_1 the A and E horizons are mixed by faunalturbation to form a single A horizon by T_2. Concomitantly the Btl horizon argilliturbates, but remains unchanged (i.e., is maintained) during T_1–T_2, which is proanisotropic pedoturbation as defined. For the profile *in general,* however, pedoturbation is of the proisotropic kind, because an A/E/B/C profile regresses to an A/B/C profile.

Hypothetical examples of proanisotropic pedoturbations

Figure 2 shows 13 profiles also at two different stages in their evolutions. In the first seven examples (Fig. 2a–g) mixing processes act in such a way that the number of preexisting horizons is maintained. Thus, even though the A horizon in Fig. 2f expands at the expense of the C, and the Bt1 horizon in Fig. 2g expands at the expense of the E, the criteria for proanisotropic pedoturbation are met because the horizons are maintained.

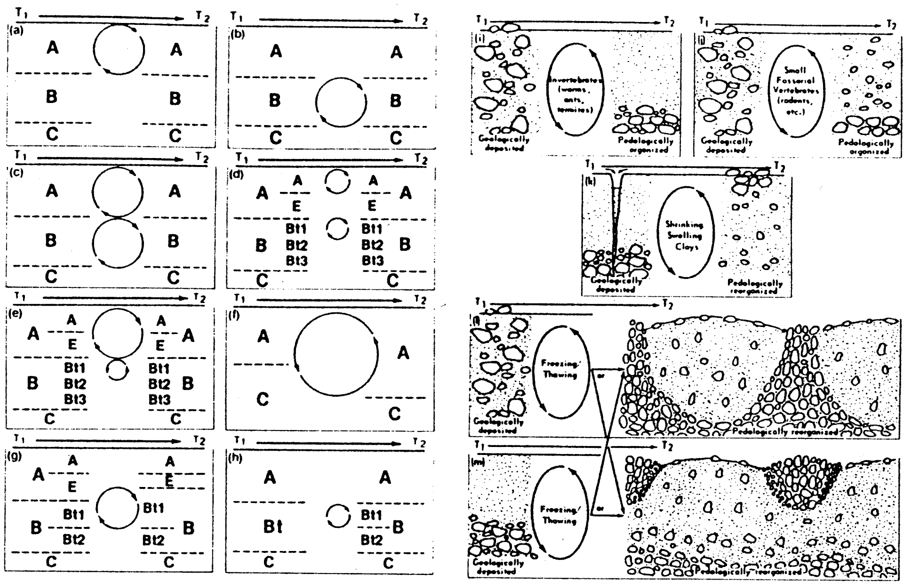


FIG. 2. Several simplified, hypothetical examples of how proanisotropic pedoturbations can occur during a period T_1 to T_2. Various mixing and organizing permutations are possible, probably more than are shown here.

Figure 2h shows that the Bt horizon at T_1, through subsurface mixing (e.g., argilliturbation), has promoted the development of a new subhorizon (Bt1) at T_2.

Figures 2i and 2j show how geologically deposited homogeneous, gravelly materials at T_1 are reorganized bimodally via faunalturbation, to gradually form a biomantle comprising a lower coarse-clast stone zone and an upper finer-clast, texturally homogeneous layer. (The earth materials at T_1 in both examples could have been heterogeneously deposited in two or more layers, and the results at T_2 after pedologic reorganization would be similar.) The different textural expressions of the two figures at T_2 reflect differences in animal-mixing vectors (invertebrates in Fig. 2i versus small vertebrates in Fig. 2j).

Figure 2k shows how geologically deposited materials, a fine-textured layer above a coarse-textured layer, can be reorganized bimodally, via argilliturbation, to a coarse-clast surface pavement over a lower, texturally homogenous layer. (If the materials at T_1 were unstratified, the results would still be similar to those shown at T_2.)

Figures 2l—2m show how geologically deposited materials, homogeneous in one case and geologically stratified in another, can be pedogenetically reorganized via cryoturbation to express profile order, surface microrelief, and spatial patterning (the right-hand portion of Fig. 2l and 2m is adapted from Jahn (1968)).

Figures 1 and 2 are hypothetical, but most of the examples are based on actual field examples, as the next section shows.

Soils that express proisotropic pedoturbations

Field expressions of proisotropic pedoturbations are widespread and readily observable in many environments. Mixing processes include those that probably are most familiar to field workers, such as argilliturbation and the various forms of bioturbation. Depending on their nature, such processes may be relatively rapid or gradual, as the following five examples show.

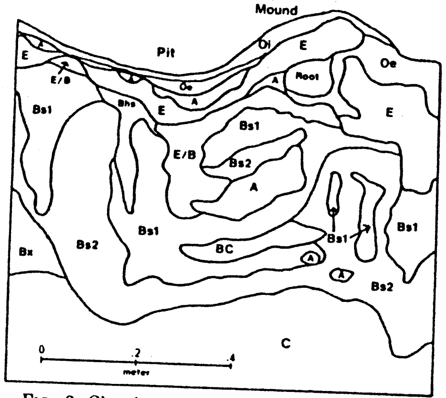


FIG. 3. Sketch of a 150-year-old tree uprooting mound and pit pair from the upper peninsula of Michigan. Complete solum mixing of a proisotropic nature in this shallow soil has occurred (from Schaetzl[5]).

Floralturbation

Treefall in nongravelly soils, upper peninsula, Michigan. Trees uprooted by storms cause sudden, severe horizon mixing—an example of rapid proisotropic pedoturbation. In and around the Ford Forestry Center near L'Anse in the upper peninsula of Michigan, tree-tip mound-and-pit topography is widespread, indicating the effects of floralturbation.[5] Where floralturbation has occurred in shallow soils, the entire solum may be mixed (Fig. 3; see Fig. 1a). The resulting soils commonly are Entic Haplorthods and Udipsamments. In deep soils with fragipans (Fragiorthods) and in Haplorthods with cemented orstein horizons, mixing usually occurs above the dense subsoil layers (Fig. 4; see Fig. 1b). Thus while floralturbation can in part determine the kind of soil present, the character of the soil—i.e., the presence or absence of dense pans—can partially determine the depth to which floralturbation can occur.

Argilliturbation

Shrinking and swelling clay soils evolved in fine-textured parent materials, San Clemente Island, California. The morphological simplicity of many A/C profiles—certain Torrerts, for example, also demonstrates proisotropic pedoturbation. Produced by argilliturbation, these profiles evolved gradually. Morphological evidence in some Torrerts and Xererts suggests that they were once more complex soils with argillic horizons (Muhs 1980, 1982; Soil Survey Staff 1975, p. 377). Muhs (1982), for example, presents evidence that 200 000-year-old Xererts on San Clemente Island, California, evolved from argillic B horizons of younger Xeralfs. According to Muhs, the B horizons gradually thickened via clay illuviation, became vertic because the clay was dominated by expandable species, then eventually engulfed their A horizons. The Xeralf stage of the process as described is indicated at T_1 in Fig. 1c, and the subsequent Xerert stage to which it evolves is at T_1 in Fig. 1a. Other workers have suggested or implied similar explanations for the origin of Vertisols elsewhere (Buol et al. 1980, p. 256; Dan and Singer 1973; Soil Survey Staff 1975, p. 377).

Argilliturbation as described above is by definition an example of proisotropic pedoturbation: horizons or soil genetic layers are destroyed, and the profile has regressed to a simpler state. Vertisols meet such conditions when the soil particle sizes are small enough to allow uniform assimilation, mixing, and blending throughout. Conversely, a Vertisol may evolve in parent materials comprising both relatively fine *and* coarse particles (clays, silts, and sands, as well as pebbles, cobbles, and boulders); then ordering and genetic layering can and probably will occur, as demonstrated later. The result is proanisotropic pedoturbation. This points out the importance of parent material particle size in determining whether some soils become ordered or not.

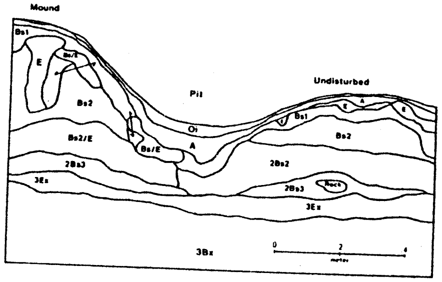


FIG. 4. Sketch of a tree uprooting mount and pit pair, upper peninsula, Michigan. The superjacent spodic sequum of the Steuben soil (Alfic Fragiorthod) has been disrupted proisotropically, whereas the more dense subjacent fragipan (3Ex and 3Bx horizons) remains undisturbed (from Schaetzl[5]).

---

[5] R. J. Schaetzl, 1987, The effects of tree-tip microtopography on soil genesis, northern Michigan, Ph.D. thesis, Univ. of Illinois, Urbana.

Faunalturbation

Wombat burrowing in mallee country, Australia. Proisotropic pedoturbation may result from the burrowing habits of large vertebrates, for example wombats in the mallee country of Australia. These powerful beasts churn the earth and create warrens that resemble clustered bomb craters, both from the ground and from high altitude (Löffler and Margules 1980). Covering many meters in surface area, the warrens are riddled with burrows that commonly measure 0.5 m or more in diameter. Wombats effectively penetrate not only the sola, but also the dense, thick (≳0.5 m) underlying calcrete and C horizon material (Fig. 5). The abundance of warrens in the region is truly staggering: some are still active; others are long abandoned and barely perceptible (Fig. 6). In fact, in some parts of the mallee, as at the Brookfield Conservation Park near Blanchetown, South Australia, it is difficult to find any ground or soil that does not show evidence of wombat burrows. Their warren sizes and densities are such that they have even been detected from space by satellite sensors (Löffler and Margules 1980). These animals clearly play a profound role not only in breaking up calcrete and mixing the soil, but also in serving (along with plants) as fragmentation agents in the calcrete brecciation process in Australia (cf. Klappa 1979, 1980).

Because such burrowing occurs throughout the entire profile, including the C horizon, the process is not captured by the examples of Fig. 1, although Fig. 1a comes closest (if the arrows extended into the C horizon, Fig. 1a would display such mixing).

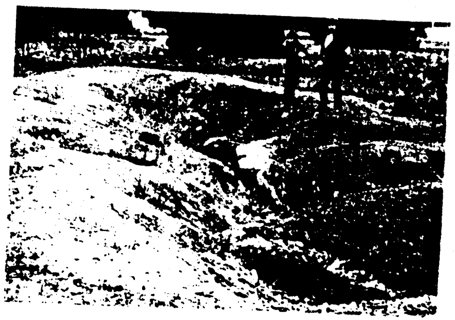


FIG. 5. Wombat warren in Brookfield Conservation Park in the mallee country of east-central South Australia, an example of proisotropic pedoturbation. Note wombat penetration of the white calcrete.

FIG. 6. Warrens representing many generations of wombats may be seen at Brookfield Conservation Park, South Australia. Coauthor D. N. Johnson (left) stands on an ancient flattened warren, while behind her is an active craterlike one. Girl (K. Johnson) at right is standing on a warren that is intermediate in age and is slightly hummocky. The abundant calcrete chunks on the surface in the photo reflect past generations of wombat burrowing.

FIG. 7. Proisotropically bioturbated Xerolls near Pleito Canyon on the north-facing slopes of the San Emigdio Mountains, Kern County, California. Ground squirrels (*Otospermophilus beecheyi*) have homogenized the soils on these slopes and are contributing to the widespread mound microrelief that dots the alluvial aprons entering the southern end of the Great Valley of California.

Ground squirrel burrowing, California. In some parts of California, ground squirrels (*Otospermophylus [Citellus] beecheyi*) are so abundant that they have an enormous effect on soil morphology and create a mima moundlike surface microtopography. Their burrows are about 10 cm in diameter and range up to 12.7 m in length and as much as 8.5 m in depth (Borst 1968). Some profiles are riddled with their burrows in the form of old and new krotovina (Fig. 7). Their activity destroys incipient subsoil horizons and prevents formation of argillic horizons. Soils that evolve under such intense mixing tend to be either Xerorthents, Entic Haploxerolls, or Xerochrepts (Rendzinas, Regosols, or 'minimal' Noncalcic Brown soils), mainly with A/C profiles.

Earth materials excavated by the squirrels form mounds up to several meters in diameter and 0.75 m high. The mounds range in particle size from clay to cobbles up to 15 cm in diameter. Apparently, however, much material is transported below surface, from new to abandoned burrows rather than to the surface (Borst 1968). Mound size is thus misleading as an estimate of the volume of material moved. Using squirrel population estimates and mean burrow volumes, Borst (1968) estimated that the animals are capable of mixing topsoil and subsoil horizons to a depth of 0.75 m in about 360 years.

Clearly, these animals are important, if not the dominant, pedogenic agents in such soils. The occurrence of A/C profiles on many Holocene and earlier geomorphic surfaces in California (Keller et al. 1985) probably reflects the proisotropic pedoturbative action of these and other rodents at such sites. Figure 1a approximates such ground squirrel mixing processes, except that burrowing often extends well into the C horizon.

Earthworm burrowing in fine-textured podzols, New Brunswick, Canada. In the course of a correlation study in New Brunswick described by Langmaid (1964), five soil sites were described, sampled, and characterized. The sites were carefully chosen for their undisturbed condition and their representative acid podzols (the soils belong to the Monquart, Caribou, and Bellefleur series). This field work took place in 1958. Three years later, in 1961, the sites were revisited. In the interim earthworms had invaded three of the five sites and had completely changed the organic and mineral horizons. The F, H, Ae(E), and part of the B horizons were destroyed and blended. In addition, changes—some drastic—had occurred in the texture, color, structure, and pH of these profiles.

A site that was not part of the original study was also investigated in 1961 (Langmaid 1964). The soil was an orthic podzol (Glassville series). Near the site was an earthworm colony of recent origin that occupied an area of 27 m². One year later the colony had enlarged to 810 m² and had completely mixed the upper layers of the virgin soil.

Figure 8 depicts the four soils before and after invasion by earthworms. In all four soils the upper horizons were blended to form a distinct, simplified single horizon with a lower boundary that was very abrupt and smooth. From a time perspective, the anisotropic integrity of some soils can thus be very tenuous indeed. Figure 1a approximates the kind of profile modifications caused by such earthworm mixing.

Soils that express proanisotropic pedoturbations

Profile expressions of proanisotropic pedoturbation are often less obvious and more complex than those of proisotropic pedoturbation. Such mixing processes probably play a far greater role in the evolution of many soil profiles than is acknowledged in most pedogenetic studies. The following five field situations include texturally differentiated profiles that reflect faunalturbation, argilliturbation, and cryoturbation. In one case both faunalturbation and argilliturbation occur simultaneously in different horizons of the same profile.

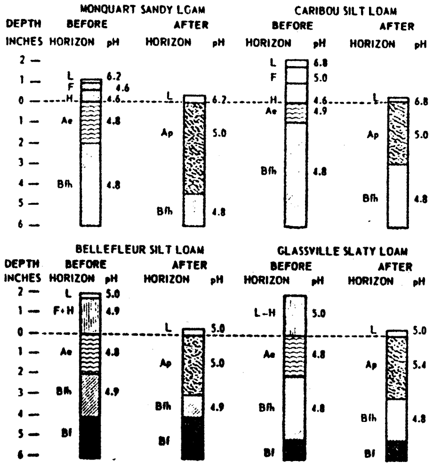


FIG. 8. Acid podzol profiles before and after mixing by earthworms (after Langmaid 1964). The Ap horizon designation indicates a disturbed layer; these were unplowed soils when studied (Langmaid, personal communication, 1985).

Faunalturbation

Earthworms and ants burrowing in soils that once had surface manuports and artifacts in England and the United States. Darwin observed that Roman artifacts, such as metal items and building stones, left on the English landscape 2000 years ago are now invariably found *within* the soil rather than *upon* it. During research to learn why, which covered many decades and included numerous experiments and observations, Darwin concluded that earthworms, mainly, were responsible (Darwin 1882). The process reflects the habit of earthworms passing soil material taken at depth through their intestinal tract, then depositing it on the surface as small mounds. Since they pass only fine fractions through their gut, any larger object will tend to be displaced downward as fines are cycled surfaceward during succeeding generations of earthworms. Given enough time, large objects will be lowered to levels that approximate the maximum depth of earthworm burrowing, which must vary spatially according to site and environmental conditions.

Darwin noted that the maximum depth of lowering he observed in his study area was approximately half a meter (he assumed surface removals via erosion had offset some of the burial effects of the worms). More recently, Johnson (1983*a*) determined that earthworms and ants in an urban setting in Illinois had buried an ungrouted brick patio several centimeters in fewer than 23 years and stepping stones 4.8 cm in fewer than 48 years. Aside from site characteristics, rate of lowering obviously would depend on earthworm types and densities, whether their churning action occurs all year or is seasonal (due to climate), the amount of offsetting surface removals via erosion, and/or the amount of geogenic surface upbuilding that might have occurred.

Such processes will cause such individual objects as artifacts, manuports, gizzard stones of birds and reptiles, and stones that were geologically deposited, to be lowered to levels dictated by site conditions. If present in adequate numbers, such objects will form subsurface horizons and layers (artifact layers, stone lines, and stone zones: Johnson 1983*a*; Johnson and Watson-Stegner 1987). A bimodally ordered biomantle thus results that consists of a lower coarse clast zone and an upper fine fraction zone (Fig. 2i).

FIG. 9. Ridge of resistant opaline silica with colluvial apron at its base on Signorelli Ranch near the end of the San Miguelito Canyon Road, Lompoc, California (see Fig. 10).

Pocket gopher burrowing in gravelly soils, Lompoc area, California. Near Point Arguello, Lompoc, California, on the Signorelli Ranch is an outcrop of fractured and jointed clastic rock composed of opaline silica. It is part of the Monterey Formation of Miocene age. Because it is relatively resistant to weathering, it forms a steep ridge with a southern, debris-covered slope almost at repose angle (Fig. 9). The rock is thinly bedded, and clasts released to the slopes by weathering are commonly tabular in shape, ranging from granules several millimeters in diameter to fist-sized and larger pieces. The clasts mass-waste down the steep slopes and are eventually delivered to a colluvial apron that lies at the base of the ridge. The clasts in the colluvial apron have been pedogenetically assimilated into a dark, organic-rich gravelly Xeroll (Johnson 1983*a*,*b*).[6] The depth of the pedogeneticized apron is unknown, but is observed to be at least 2 m deep in a recent borrow pit. Exposed in the wall of the borrow pit is a conspicuous stone zone consisting of coarse silica clasts (> 7 cm in long axis diameter) within a matrix of smaller clasts (< 7 cm) and dark soil (Fig. 10). The stone zone is also visible in road cuts leading to the pit. The tabular coarse clasts that form the stone zone show random orientation, although new clasts migrate down the ridge slope onto the apron with their flat sides generally parallel to the apron surface.

---

[6] D. L. Johnson, Subsurface stone lines, stone zones, artifact-manuport layers, and biomantles produced by faunalturbation via pocket gophers (*Thomomys bottae*), unpublished manuscript.

When the site was studied in 1982, the colluvial apron was covered with the mounds of pocket gophers (*Thomomys bottae*). Analysis of 11 mounds revealed that all had clasts less than 7 cm in long axis diameter. Further, the borrow pit wall had fresh, unfilled gopher burrows from the surface to a depth of 2 m, though most burrowing was higher in the profile. (Burrows of *Thomomys* average 6 to 7 cm in diameter.) Particle size and organic-matter analyses of the fine fraction (< 2 mm) from three pedons exposed in the borrow pit wall showed similar depth functions above and through the stone zone (Fig. 11), which are best explained by mixing.

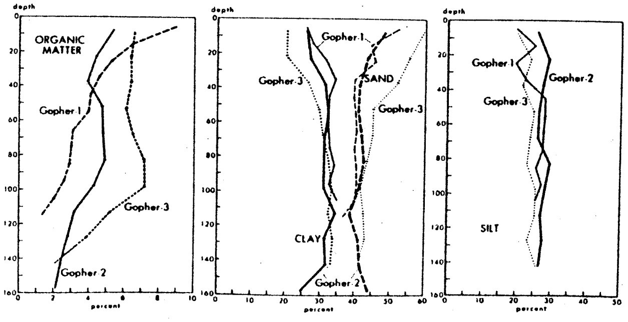
Clearly the gophers have thoroughly homogenized the soil fraction that can be moved through their burrows—particles less than 7 cm in long axis diameter. In this way, as gophers bring smaller clasts and soil to the surface, the coarser clasts that they cannot move upward gradually settle downward and become concentrated as a stone zone. Random orientation of the rocks thus lowered and that make up the stone zone is thought to reflect jostling as the finer materials around them are cycled upward. The result is a clast-dominated, layered profile with a gross morphology that reflects proanisotropic pedoturbation. The process is modeled in Figs. 2j and 12.

FIG. 10. Stone zone of coarse clasts (> 7 cm) in a matrix of smaller clasts and dark soil (Xerolls) formed by proanisotropic pedoturbation via pocket gophers (*Thomomys bottae*), Signorelli Ranch, Lompoc, California (see Fig. 9) (after Johnson 1983*b*).

Faunalturbation and argilliturbation

Gopher burrowing in manuport- and artifact-bearing topsoils, and shrinking and swelling of clays in subsoils, Point Conception, California. About 20 km south of Lompoc on the California coast near Point Conception, is the Conception soil, an Argialboll-Natralboll formed under a seasonably moist/dry climate. The soil has evolved in late Pleistocene fluvial deposits many meters thick that overlie raised marine platforms (Johnson 1981; Johnson and Rockwell 1982). Archeological materials occur intermittently over this surface, which slopes gently to the south toward beach cliffs. The loamy topsoil has been mixed by pocket gophers (*Thomomys bottae*), as indicated by abundant gopher mounds on the surface and by krotovinas on the side walls of the soil profiles. The loamy, pale, leached E horizon shows signs of seasonal wetness (mottling, small shot-sized MnO_2 and Fe_2O_3 concretions). In some pedons, within the perimeter of an archaeological site (Ca-SBa-1502), a stone line consisting of boulders and cobbles greater than 7 cm in diameter occurs in the E horizon: the stones are believed to have been brought into the site by humans (Clewlow 1981). Gopher-sized krotovinas occur in the A and E horizons, though they are less abundant in the latter. The presence of the krotovinas, the stone line, and the uniform loamy texture of the fine fraction throughout both the A and E horizons suggest vertical, between-horizon mixing by gophers, although not at rates high enough to cancel visual and chemical overprinting by the more rapid and intense lateral (mainly) leaching processes within the E horizon. A strong textural contrast occurs between the loamy E and clayey Bt horizons and is marked by a very abrupt smooth boundary.

FIG. 11. Depth functions of organic matter and particle size of three Xeroll profiles in gravel borrow pit on Signorelli Ranch, upper San Miguelito Canyon Road, Lompoc, California (data from Tables 16–20 in Johnson 1983*b*).



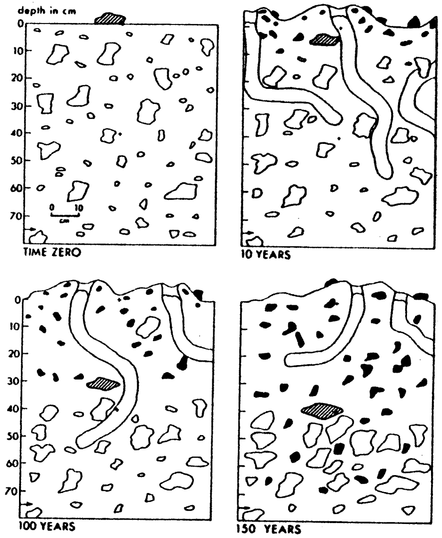


FIG. 12. Model of stone zone formation due to pocket gopher burrowing based on a hypothetical sequence of events and timing. For simplicity, time zero assumes uniform distribution of stones of different sizes. Large hatched stone is a manuport dropped by humans. Stones that have diameters 6–7 cm (the maximum diameter of gopher burrows) or less and that have been translocated to the surface at least once by gophers are shown in black. The two crosses are constant reference points. Arrow indicates maximum depth (75 cm) to which gophers burrow in this particular soil (in other soils they may burrow more or less deeply). Eventually a 40-cm thick zone of stones larger than 7–8-cm-diameter forms at the 30–75-cm-depth. The zone of complete faunalturbation after 100 or so years is from the surface to maximum depth of burrowing. The large stone at the 10-cm depth in the 100-year profile could have been another manuport dropped later, could have been delivered to the site via mass wasting or other process, or could have been dug from the stone zone by a larger mammal (badger, ground squirrel, etc.) and then reburied by pocket gophers. (Burrow geometry and depth as shown are meant to suggest their average character; burrow bottoms may not necessarily terminate as shown, but may extend away from or toward viewer; modified from Johnson 1983b.[6])

The Bt horizon, which lacks krotovina, is physically and chemically differentiated into three subhorizons. The Bt1 horizon is dark and clayey (50 to 60% clay) with strong, medium columnar structure. The clay fraction is dominated by expandable species and decreases in amount downward into the Bt2 and Bt3 horizons. The latter two horizons show signs of seasonal wetness (mottling, gleying). Clay films are relatively thin and few in the upper Bt horizon, but thicken and increase in coverage in the lower Bt. Pedoslickensides and remnants of stress cutans (plasma separations) occur abundantly in the Bt1 horizon—indicating argilliturbation in this layer—but are absent from the Bt2 and Bt3 horizons.

For these and other reasons, Johnson (1981)[6] and Johnson and Rockwell (1982) concluded that gopher burrowing texturally differentiates the upper profile into a biomantle (< 7 cm) whose lower portion contains a stone line. As mentioned, the process is visually and chemically overprinted by seasonally intense lateral leaching processes that differentiate the eluvial E horizon. We interpreted the stones as manuports originally left on the surface by humans that were lowered to their present level in the E horizon by gopher burrowing (Fig. 13). We further concluded that argilliturbation occurs in the Bt1 horizon, and that when wetted the Bt1 horizon swells and seals, becoming an aquiclude that inhibits vertical soil water percolation and thereby promotes saturation and intense lateral (downslope) leaching in the overlying E horizon. The complex processes of proanisotropic pedoturbation in this profile are shown in Fig. 2e.

Argilliturbation

Shrinking and swelling clay soils evolved in parent materials of widely varying particle sizes, Channel Islands and adjacent mainland, California. About 40 km south of Point Conception, across the Santa Barbara Channel, lies San Miguel Island. Pelloxererts on the east end of the island have evolved in marine and eolian sediments that thinly veneer the subjacent, raised, gently sloping marine planation platforms. The soils studied have never been cultivated. They

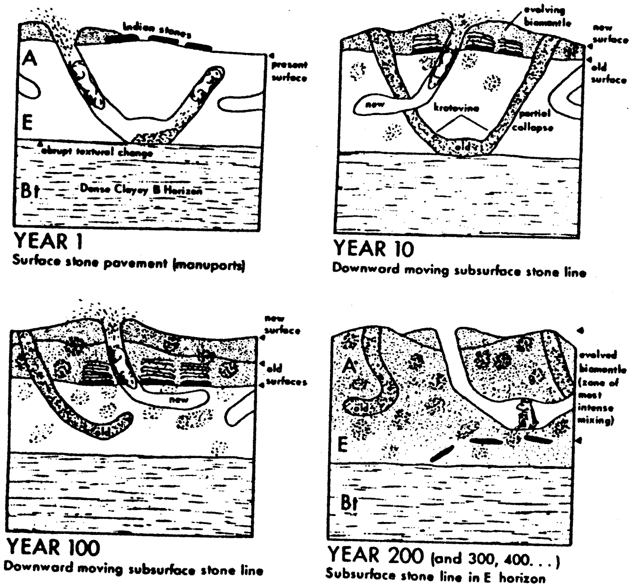


Fig. 13. Sequential model showing how artifacts and other large surface stones are lowered through the A horizon to the E horizon by pocket gopher burrowing. The dense, clay-rich Bt horizon is not burrowed. Soil and clasts smaller than 7 cm in diameter are recycled to the surface by the rodents. The time frames indicated are suggested on the basis of a previous study (modified from Johnson 1981).

are uniformly clayey and dark, and laboratory characterizations show remarkably uniform depth functions of particle size, clay mineralogy, and organic matter (Johnson 1972). A pavement occurs on the surface of some soils consisting predominantly of cobbles and boulders that show evidence of rounding by wave action, some of which show boring by marine organisms (Figs. 14 and 15).

Similar uncultivated soils (Pelloxererts/Chromoxererts) with surface pavements of rounded stones occur on certain raised marine terraces on San Clemente Island (those on this island without pavements were discussed earlier as examples of soils that express proisotropic pedoturbation). The mainland soils on the Palos Verdes peninsula near San Pedro resemble the island soils, except that they have been cultivated and their surface stones removed and piled along field edges and gullies. These stones also are wave-rounded, and some are marine-bored.

Modern analogues of the processes that produce rounded, bored clasts are found on active marine platforms in the wave zones of the Channel Islands and the Palos Verdes peninsula. If these modern platforms were uplifted and subaerially exposed, they would resemble Stage 1 of Fig. 16 (Johnson and Hester 1972). The hypothetical origin of the island Vertisols and their surface stone pavements, and the mainland Vertisols before their pavements were removed, is illustrated in Fig. 16. (Some evidence suggests that Stages 2–4 may have evolved along a more complicated, Natrixeralf to Pelloxerert/Chromoxerert, profile-simplifying pathway; if so, the process may qualify as proisotropic pedoturbation, even though a stone pavement is produced [see previous section and Discussion and Muhs 1982]). Figure 17 shows in more detail how the process in Stage 4 of Fig. 16 works given annual, wet/dry seasons. Stages 2–4 are included in the T_1–T_2 timespan of Fig. 2k. Other studies have led to similar conclusions regarding the genesis of surface-concentrated stones, surface concretions (e.g., calcrete nodules), and other materials on and in Vertisols (Bryan 1947; Dudal 1965, p. 78; Johnson et al. 1962; Yaalon and Kalmar 1978).

Fig. 14. A Pelloxerert terrain on a raised marine terrace, east-central San Miguel Island, California. A soil pit (0.9 m²) excavated at 15-cm depth intervals revealed that the largest clasts were concentrated in the upper sola. The pile of stones on the left behind the soil pit came from the upper 15 cm, those on the right from the 15–30-cm interval. Stones from the 30–45-cm interval are not shown, but were about half the number of the 15–30-cm interval (see Fig. 15).

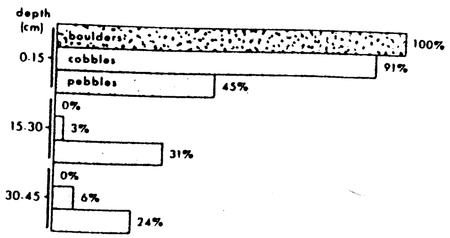


Fig. 15. Histogram showing the relative number and size of boulders (> 256 mm), cobbles (64–256 mm), and pebbles (4–64 mm) taken from the 0–15, 15–30, and 30–45-cm depth levels of the Pelloxerert shown in Fig. 14 (after Johnson 1972 and Johnson and Hester 1972).

Cryoturbation

Freezing and thawing of patterned ground soils with widely varying particle sizes, cold climates. Patterned ground, usually with microrelief expression, typifies many cold lands of our planet. A. L. Washburn introduced the term *patterned ground* to describe "... more or less symmetrical forms, such as circles, polygons, nets, steps, and stripes, that are characteristic of, but not necessarily confined to, mantle subject to intensive frost action" (Jahn 1968). It most commonly develops in the active layer of permafrost, i.e., ground deeply frozen all year that thaws during summers in the upper 0.5–1.5 m.

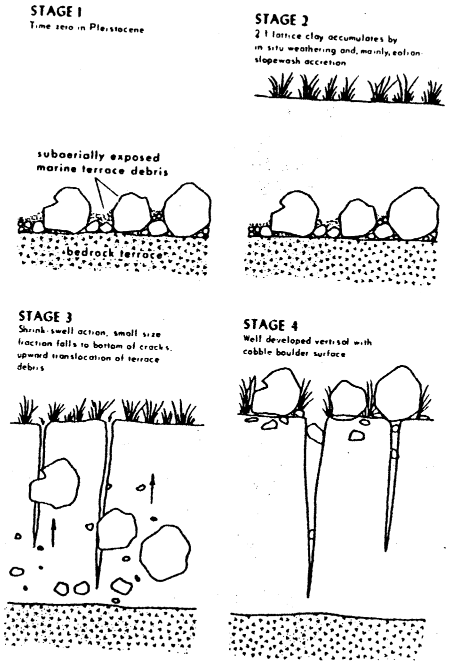


Fig. 16. Hypothetical model showing a subaerially exposed, tectonically raised marine terrace platform (Stage 1) that gains a soil via allochthonously derived silts and clays (Stage 2). At some point, the soil begins argilliturbating (Stage 3) and eventually evolves to a Pelloxerert with a surface stone pavement composed mainly of clast sizes that, once forced upward, are too large to recycle down the cracks (Stage 4) (after Johnson 1972, and Johnson and Hester 1972).

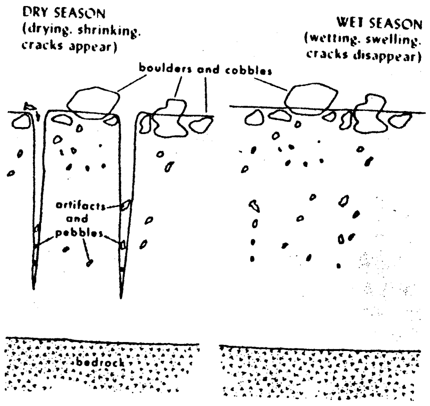


Fig. 17. Model showing more detail of the annual, wet-dry seasonal shrink-swell processes of Stage 4 in Fig. 16.

The principal process involved in promoting patterned ground is repeated freezing and thawing of soil. Saturation of the soil, e.g., Cryaquepts, by melt water and the absence of vegetation further stimulate its formation (Jahn 1968). On variably textured soils such action causes coarser clasts to be shifted toward freezing surfaces, either upward toward the surface or laterally toward frost cracks, which develop as the ice thermally contracts at low temperatures (below −10°C). In time, originally homogeneous or geologically stratified parent material will pedologically reform to patterned ground, as shown in Fig. 2l–2m.

DISCUSSION

Mixing processes (Table 1) may function either proisotropically or proanisotropically. Argilliturbation, for example, may produce a disordered profile (or profiles) in one soil or polypedon (Fig. 1a), a more ordered profile in another (Fig. 2h), or vice versa. This can be true not only for different soils on a landscape, but also for the same soil at different times during its evolution. For example, in a Natrixeralf profile with an argilliturbating (vertic) Bt horizon (Fig. 2h), the Bt may thicken both through illuviation and by gradual incorporation of the E or A horizon (Fig. 2g). The Bt horizon eventually engulfs first the E horizon (Fig. 1c), then the A (Fig. 1a): the soil has become a Vertisol. The sequence shows hypothetically the evolution of a soil first along a predominantly progressive Entisol to Alfisol pathway, and later along a predominantly regressive Alfisol to Vertisol pathway. In *real* soil landscape situations, however, evidence for either pathway or other pathways may be equivocal or absent. This is probably the case for many, if not most, soils and soil landscapes. Thus, the California Vertisols that had stone pavements formed on some pedons were cited as examples produced by proanisotropic pedoturbation. This interpretation, however, was based on the model of Fig. 16, which is hypothetical. On the other hand, if Muhs' suggestion that the genetic pathway may have included an Alfisol to Vertisol component is correct (Muhs, 1982), the examples reflect proisotropic pedoturbation. A Natrixeralf that evolves to a Pelloxerert, even one with an evolved pavement, reflects a probable overall decrease in soil order, whereas in Fig. 16 order increases with time.

The above examples underscore the point made earlier that firm evidence of prepedoturbation (T_1) morphologies often may be equivocal or lacking. If such is the case, deciding whether a profile reflects predominantly proisotropic or proanisotropic pedoturbation would then become subject to observer interpretation. Resolution of this problem is largely provided by the way proanisotropic pedoturbation is defined; if evidence for overall profile simplification is lacking, and mixing causes or substantially aids in causing horizons or genetic layers to form or be maintained, the process is assumed to be proanisotropic.

Because proanisotropic pedoturbation can reorganize homogeneous or heterogeneous geologic deposits into pedogenic layers, the concept of "lithologic discontinuities" in soil profile descriptions becomes problematic. The concept has been traditionally used to indicate layers of contrasting materials, normally geologic materials, denoted by either Roman or Arabic numerals: does it also apply to texturally different layers that are entirely of pedogenic (pedoturbative) origin and have nothing whatsoever to do with conventionally assumed superposition or deposition via alluvial, colluvial, or eolian burial processes (e.g., Fig. 2i–2m)?

It is clear that the nature of the initial parent material is an important factor in determining the morphologic expression of some pedoturbated soils. If, for example, the colluvial apron on the Signorelli Ranch near Lompoc, California, in which Xerolls formed had been composed of fine-textured materials or coarse-skeletal materials less than 7 cm in diameter (i.e., smaller than the diameter of gopher burrows), no differential size-sorting by gophers could have occurred. Likewise, if no coarse clasts were present in the marine terrace Vertisols of California or in the Cryaquepts of permafrost zones, no surface stone pavements or stone-bordered polygons could have formed. In each case parent material particle size in conjunction with the form of pedoturbation determined whether the ensuing profiles expressed morphologic order or disorder. If, for example, the California Xerolls and Vertisols discussed above had been faunalturbated by a wombat-sized animal, or if they were nongravelly soils that experienced tree uprooting, disordered profiles would have resulted. By the same token, if Darwin's earthworms had faunalturbated soils without large artifacts, no subsoil artifact horizons could have formed.

A comparison of the burrowing habits of ground squirrels versus pocket gophers is illuminating. Though they make mounds, much of the activity of ground squirrels appears to involve moving excavated material from new to old holes *within* the soil. Pocket gophers, conversely, appear to move most excavated material *from* the soil to the surface. Thus in gravelly parent materials, because of their different burrowing habits, gophers tend to pedoturbate proanisotropically, other things being equal, whereas ground squirrels tend to pedoturbate proisotropically.

Floralturbation via tree uprooting in nonstony soils in the upper peninsula of Michigan is an example of proisotropic pedoturbation. However, if tree uprooting occurs in stony soils, or soils that are shallow to bedrock, a surface or near-surface concentration of stones may be produced (Denny and Goodlett 1956, p. 64). In such soils rock fragments commonly are entangled in the upthrown roots of trees, and when the roots decay or are destroyed by fire the stones are released to the soil surface. This surface-concentration process is augmented by rainwash of bare, unprotected mounds that are created in the uprooting process. As fines are washed away, stones in the mounds and upheaved with them accumulate as lag on the surface. Such processes are accelerated on steeper, more erosion-prone slopes. If such armored surfaces are buried, and deeply enough that later uprooting events do not rework them, they become *stone lines* or *stone zones* in the pedostratigraphic record. Such processes, together with the various hypothetical and real soil examples given earlier, provide insights into the possible range of origins of stone pavements, armored surfaces, stone lines, and stone zones that occur on all continents in many different environments.

CONCLUSIONS

Concepts are indispensable tools of scientific communication and often reflect the state of knowledge of a science. Two of their important and useful aspects are the degree of specificity and the relative levels of conceptual complexity that they convey. The term-concept *pedoturbation*, for example, simply denotes soil mixing. The term-concept *argilliturbation* conveys a higher degree of specificity by indicating the genetic type of mixing. The expression *proanisotropic pedoturbation*, on the other hand, carries a much broader level of conceptual complexity than does either of the other terms. It connotes mixing processes in a profile that are at least partially responsible for the formation or maintenance of one or more of its horizons or genetic layers, and for aiding in the profile differentiation process. Attributes of profile morphology and the genetic linkage between morphology and process are thus both conveyed.

The worth of any pedologic concept is whether it is valid and helps explain one or more aspects of the soil system. Its validity and utility are increased if, in addition, it aids in the generation of new ideas, testable hypotheses, and general truths. Ideally, the concept would do all these, plus aid in prediction.

The theoretical formulations presented here are an attempt to fine-tune the concept of pedoturbation in a theoretical framework of soil evolution. They derive largely from our repeated field observations of profiles affected by mixing. We think the formulations break new conceptual ground in that they call attention to how pedoturbation processes can affect soil morphology in both regressive (proisotropic) or progressive (proanisotropic) fashions. Genetic relationships between particle size, forms of pedoturbation, and the overall resulting morphologic and surface expressions of soils are clarified. A different perspective of soil genesis is thus gained, which should aid in pedogenetic interpretations, in generating ideas, and perhaps even in prediction.

ACKNOWLEDGMENTS

We thank C. S. Alexander, F. D. Hole, and D. R. Muhs for critically evaluating and offering suggestions on this manuscript, J. Bier for cartography, and B. Bonnell for typing.

REFERENCES

Borst, G. 1968. The occurrence of crotovinas in some southern California soils. Trans. 9th Int. Congr. Soil Sci., Adelaide 2:19–22.

Bryan, W. H. 1947. The geologic approach to the study of soils. Rep. 25th Meeting Aust. N.Z. Assoc. Adv. Sci., Aug. 1946. Adelaide, pp. 52–69.

Buol., S. W., F. D. Hole, and R. J. McCracken. 1980. Soil genesis and classification. Iowa State Univ. Press, Ames.

Clewlow, C. W., Jr. 1981. Archaeological test excavations and some lithic analyses of materials from Tc and Tw localities. Technical report for WLNG Terminal Associates, 810 So. Flower Street, Los Angeles. (Report on file at Ancient Enterprises, Inc., P.O. Box 5138, Santa Monica, Calif.)

Dan, J., and A. Singer. 1973. Soil evolution on basalt and basic pyroclastic materials in the Golan

Heights. Geoderma 9:165–192.

Darwin, C. 1882. The formation of vegetable mould through the action of worms. Appleton, New York.

Denny, C. S., and J. C. Goodlett. 1956. Microrelief resulting from fallen trees. *In* Surficial Geology and Geomorphology of Potter County, Pennsylvania. C. S. Denny (ed.). Geol. Surv. Prof. Paper 288, U.S. Gov. Print. Off., Washington, pp. 59–68.

Dudal, R. 1965. Dark clay soils of tropical and subtropical regions. FAO Agric. Devel. Paper no. 83. FAO, U.N., Rome.

Hole, F. 1961. A classification of pedoturbations and some other processes and factors of soil formation in relation to isotropism and anisotropism. Soil Sci. 91:375–377.

Jahn, A. 1968. Patterned ground. *In* Encyclopedia of geomorphology. R. W. Fairbridge (ed.). Reinhold, New York, pp. 814–817.

Johnson, D. L. 1972. Landscape evolution on San Miguel Island, California. Ph.D. thesis, Univ. of Kansas, Lawrence. (Univ. Microfilms, Cat. no. 73-11902, Univ. of Michigan, Ann Arbor, Mich.).

Johnson, D. L. 1981. Report and analysis on the Beach Fault trench soil, LNG Site, Point Conception, California. Analysis of Data: Marine Terrace Studies and Age Dating, Final Geoseismic Investigations, Proposed LNG Terminal, Little Cojo Bay, California, for WLNG Terminal Associates, Dames and Moore, Consultants, Appendix A.4.

Johnson, D. L. 1983*a*. Origins of subsurface stone lines and surface stone pavements: Biotic and abiotic examples from western and midwestern United States. Geol. Soc. Am. Abstr. Programs, 15:212.

Johnson, D. L. 1983*b*. Quaternary geology and soils of lower San Antonio Creek and adjacent areas, Vandenberg Air Force Base, California. Geotechnical Rep., Dept. of Anthropology, Univ. of California, Santa Barbara, Calif.

Johnson, W. M., J. G. Cady, and M. J. James. 1962. Characteristics of some brown Grumusols of Arizona. Soil Sci. Soc. Am. Proc. 26:389–393.

Johnson, D. L., and N. C. Hester. 1972. Origin of stone pavements on Pleistocene marine terraces in California. Proc. Assoc. Am. Geogr. 4:50–53.

Johnson, D. L., and T. K. Rockwell. 1982. Soil geomorphology: Theory, concepts and principles with examples and applications on alluvial and marine terraces in coastal California. Geol. Soc. Am. Abstr. Programs, 14:176.

Johnson, D. L., and D. Watson-Stegner. 1987. Evolution model of pedogenesis. Soil Sci. (*in press*).

Keller, E. A., R. L. Zepeda, D. M. Laduzinsky, D. B. Seaver, E. X. Zhao, T. K. Rockwell, and D. L. Johnson. 1985. Late Pleistocene-Holocene chronology for evaluating tectonic framework and events, Transverse Ranges, California. Final Tech. Rep. U.S. Geol. Surv. (Contract no. 14-08-0001-21829).

Klappa, C. F. 1979. Comment and reply on 'Displacive calcite: Evidence from recent and ancient calcretes.' Geology 7:420–423.

Klappa, C. F. 1980. Brecciation textures and tepee structures in Quaternary calcrete (caliche) profiles from eastern Spain: The plant factor in their formation. Geol. J. 15:81–89.

Langmaid, K. K. 1964. Some effects of earthworm invasion in virgin podzols. Can. J. Soil Sci. 44:34–37.

Löffler, E., and C. Margules. 1980. Wombats detected from space. Remote Sensing Environ. 9:47–56.

McHone, J. F. 1986. Terrestrial impact structures: Their detection and verification, with two new examples from Brazil. Ph.D. thesis, Univ. of Illinois, Urbana.

Muhs, D. R. 1980. Quaternary stratigraphy and soil development, San Clemente Island, California. Ph.D. thesis, Univ. of Colorado, Boulder.

Muhs, D. R. 1982. A soil chronosequence on Quaternary marine terraces, San Clemente Island, California. Geoderma 28:257–283.

Soil Survey Staff. 1975. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys: Agric. Handbook 436, Soil Conservation Service, USDA.

Wood, W. R., and D. L. Johnson. 1978. A survey of disturbance processes in archaeological site formation. *In* Advances in archaeological method and theory, 1. M. J. Schiffer (ed.). Academic Press, San Francisco, pp. 315–381.

Yaalon, D. H., and D. Kalmar. 1978. Dynamics of cracking and swelling clay soils: Displacement of skeletal grains, optimum depth of slickensides, and rate of intra-pedonic turbation. Earth Surface Proc. 3:31–42.